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SURFACE WELDING IN THE SPACE ENVIRONMENT

DEFENSE METALS INFORMATION CENTER

BATTELLE MEMORIAL INSTITUTE

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SURFACE WELDING IN THE SPACE ENVIRONMENT

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SUMMARY

While there appears to be a real potential for welding metals in space as a means of assembly, most of the work to date has been concerned with preventing such occurance. Solution of the problems of lubrication of moving parts in space environment has taken precedent over direct studies concerned with adhesion and cohesion.

Much of the research on welding in space has been directed toward learning fundamentals, such as affects of surface conditions, temperature, and physical properties on adhesion of materials. This basic information now needs to be applied to those alloys that are useful to the designer.

Investigations are all influenced by the mechanics of simulating space environments and in maintaining them for significant lengths of time. There is now a need to standardize both the methods of space simulation and the test specimens. Until this is done, more will be learned from actual space flights than from ground-based simulations.

INTRODUCTION

In this memorandum, the available reports in DMIC which are concerned with welding of metal surfaces in space environments, whether this welding is desirable or undesirable, are reviewed. It has been compiled because of numerous inquiries on the subject over the past several months and as a result of an effort to gather as much information as possible that would be useful in answering these inquiries. No attempt has been made to present more than a summary of the work reported to DMIC. Interpretation or comments on the data reported have not been possible as yet. Some obvious conflicts are apparent in the data obtained by different investigators and even in the data of single investigators.

The phenomenon of surface welding in the space environment is of interest to many for various reasons. Some hope to use the phenomenon for the completion of attachment joints or repairs to spacecraft. Some are concerned because of the possible malfunction of moving components such as bearings, valves, and electrical contacts.

The space environment is unique. It is difficult to study on earth. One reason is that no single set of conditions represents more than a small portion of the space environment. The tabulation below, for example, shows the variation in some characteristics of the space vacuum with altitude.

Altitude, miles	Pressure, mm Hg	Temperature, F	Concentrating Particles, cm^3	Composition
Sea level	760	-40 to 105	2.5×10^{19}	78% N_2, 21% O_2, 1% A
20	10^1	-40	4×10^{17}	N_2, O_2, A
125	10^{-6}	10^3	10^{10}	N_2, O, O_2, O^+
500	10^{-9}	10^3	10^6	O, O^+, H
4,000	10^{-13}	10^3	10^3	H^+, H
Above 4,000	10^{-12}	10^3 to 10^5	10^1 to 10^2	85% H^+, 15% He^{++}

Temperatures shown in this tabulation are those of the gas and have no significant effect on the temperature of the vehicle. Most metals and metallic alloys are quite stable in the space vacuum from an engineering-strength standpoint. However, surface properties will change significantly with extended exposure. The <u>surface</u> properties of a metal largely govern the ease with which welding will occur.

Metals can be welded by merely bringing their surfaces into intimate contact. This does not happen normally, because two things prevent actual contact of the metallic surfaces:

(1) Metal surfaces are not clean. The surface of a metal is normally coated with films of oxide, contaminants, or absorbed gases.

(2) Metal surfaces are not flat. The surface of a metal is normally very rough on a microscopic scale. This roughness prevents actual contact at all but a few points.

In terrestial applications, true metal-to-metal contact can be avoided or utilized as needed. Lubricants of many types are available to minimize wear. Coatings are available to prevent welding when necessary. Even the terrestial environment is conducive to the minimization of metal-to-metal contact through the formation of oxide and adsorbed gas films on metals. Methods are also available to prepare surfaces for welding when desired. In space none of these relatively simple methods of controlling the operating characteristics of devices such as bearings and valves, preventing welding of contacting metal surfaces when undesirable, or causing welding to occur when desirable is available. Lubricants must be very carefully chosen for reliable operation in the space environment because they evaporate or lose their efficiencies. Seizing in bearings or valves may result. Oxides or other coatings which prevent welding of contacting surfaces may also evaporate or may diffuse away from the surface and not be reformed. Thus, welding may result, which will prevent later desirable separation.

It can be seen from the above that the subject "welding-in-space" can be quite broad. For complete coverage many subjects must be covered. A few of these are: materials differences such as composition, hardness, and strength; surface conditions such as roughness, crystalline structure, and residual surface contaminants; basic properties such as the coefficient of friction between similar and dissimilar metal couples; lubricants, if present, and their stability; temperature effects; and effect of radiation and exposure times.

Most investigatiors who are concerned with studying the effect of having two metals in contact in a simulated space environment refer to the adhesion and cohesion of the two materials. The results are usually reported in some form that utilizes the coefficient of friction or in the strength of bonds attained under standardized conditions for a particular method of contacting the surfaces and determining

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the desired parameters. All investigators are influenced by the difficulty in suitably simulating space environments and in their maintenance, lack of standardized practice, and the requirements of their program objectives. Thus, in spite of the fact that many studies applicable to the welding-in-space phenomenon have been made and are in progress, little direct correlation of the reported results is possible. Consequently, in this review the viewpoint has been taken that the best way to cover the available literature is to cover each item individually. To do this, extensive direct quotations of important information from final reports or the latest available progress reports have been used. The emphasis is placed on those studies involving bare metal-to-bare metal contact and of commercial materials in particular. Lubricants, lubrication, coatings, and test equipment studies are covered by an appended, annotated bibliography.

The available literature on solid-state welding (diffusion bonding, cold welding, etc.) and friction, wear, and lubrication forms an important basis for much of the understanding of surface welding in space. The interested reader should consult the many available references on these subjects to aid in developing an understanding of the important phenomena controlling metal surface welding.

RESEARCH AT THE HUGHES AIRCRAFT COMPANY

In early work at Hughes Aircraft, the effect of surface contaminants on the ability to prevent seizure between metal surfaces at 2×10^{-9} torr was demonstrated.[(1)*] A pointed rod of cold-rolled steel could not be made to stick (weld) to a flat surface of the same material even after 75 days at room temperature. Induction heating the steel to 1650 F and holding for 1-1/2 hours to degas the surface, followed immediately by scratching the two specimen parts together, caused seizure. The strength of the resultant joint was about 45,000 psi. The need for vacuums that are much better than 10^{-9} torr to fully evaluate metal-to-metal welding was shown when the degassed specimen was allowed to stand for 0.5 hour, after which seizure could no longer be realized.

Subsequent studies at Hughes for NASA have been directed toward the determination of the temperature, time, and conditions that cause adhesion or cohesion between metallic materials, including structural metals in a vacuum.[(2,3)] They define adhesion as "the molecular attraction exerted between the surface of separate bodies in contact", and cohesion as "the molecular attraction by which particles of a single body are united throughout the mass, whether the particles are like or unlike". However, for their purposes, bonding of like materials is called cohesion, while bonding of unlike materials is called adhesion.

The early portion of the first year's work on this program was used for the design and fabrication of a vacuum test chamber incorporating these features: (1) an environmental pressure not greater than 5×10^{-9} torr, (2) a loading device capable of providing and measuring tensile and compressive loads of from 0 to 100,000 psi, and (3) a range of test temperatures from 25 to 500 C.

Tests were made in this equipment by the application of compressive loads to contacting test specimens in the vacuum chamber for a given time. Then, the tensile force required to separate the two specimens was measured to determine the extent of adhesion or cohesion.

Thirteen different combinations of metal couples were evaluated. Loads equivalent to 80 percent of their compressive yield strengths at test temperature for times to about 2 hours were used.

The method of preparing specimens was as follows: machine and surface grind to a finish of 32 ± 5 rms; degrease by standard military specification techniques. Place in vacuum chamber, pump down, and bake out at the temperature which is to be used for bonding the specimen. Bake out is continued until the pressure reaches 5×10^{-9} torr, after which it is held for 6 hours before the contacting surfaces are contacted.

Under these conditions the following couples did not bond at 500 C:

(1) 304 steel to 304 steel, (2) 304 steel to A286 steel, (3) 304 steel to René 41, (4) A286 steel to A286 steel, (5) René 41 to René 41, (6) Ti-6Al-4V alloy to René 41, and (7) A286 steel to René 41.

The following couples did not bond at 300 C:

(1) 2014 aluminum to Ti-6 alloy, (2) 2014 aluminum to 304 steel.) Ti-6Al-4V alloy to Ti-6Al-4V alloy.

Copper formed a weak bond to itself at temperatures as low as 300 C. The 2014 aluminum showed a tendency to bond to itself, René 41, and A286 at 300 C.

Data collected as a result of this study at various times and at various temperatures are recorded in Figures 1, 2, and 3.

For the second year's work in this program, the equipment was modified for conducting dynamic tests in which one of the specimen parts was oscillated ± 2 degrees at 3 cps against the other (stationary) specimen part, while under compressive load. The couples tested in the altered equipment are listed in Table 1. All couples were tested under static conditions, but only the first 11 were tested under dynamic conditions. As expected, adhesion and cohesion occurred more readily in the dynamically loaded tests than in the static tests.

Under dynamic loading conditions, the following couples bonded at room temperature:

(1) A286 steel to A286 steel, (2) 304 steel to 304 steel, (3) René 41 to René 41, (4) Ti-6Al-4V alloy to Ti-6Al-4V alloy, and (5) copper to copper.

The following couples did not bond at room temperature, but did bond at 150 C:

(1) 2014 aluminum to 2014 aluminum, (2) 304 steel to 2014 aluminum, (3) 304 steel to René 41, (4) 2014 aluminum to René 41, (5) 2014 aluminum to A286 steel, and (6) 2014 aluminum to Ti-6Al-4V alloy.

* References are listed on pages 13 and 14.

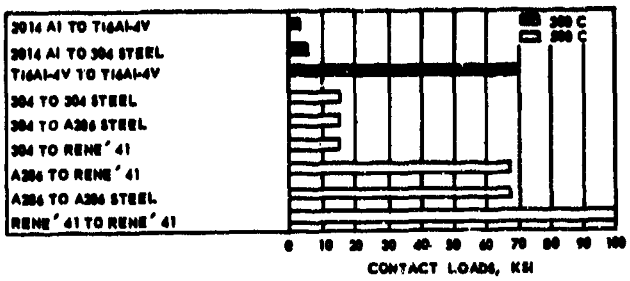

FIGURE 1. MAXIMUM LOADS AND TEMPERATURES UNDER WHICH ADHESION OR COHESION DID NOT OCCUR IN 70,000 SECONDS(2)

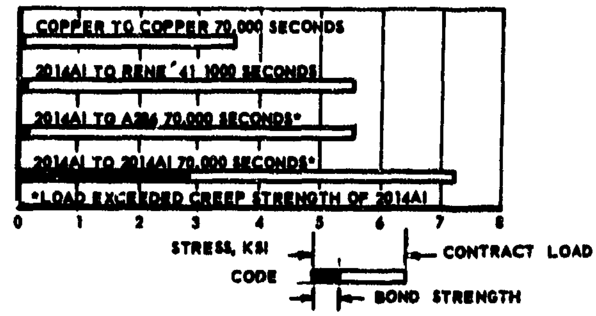

FIGURE 2. BOND STRENGTH OF COUPLES THAT ADHERED OR COHERED AT 300 C(2)

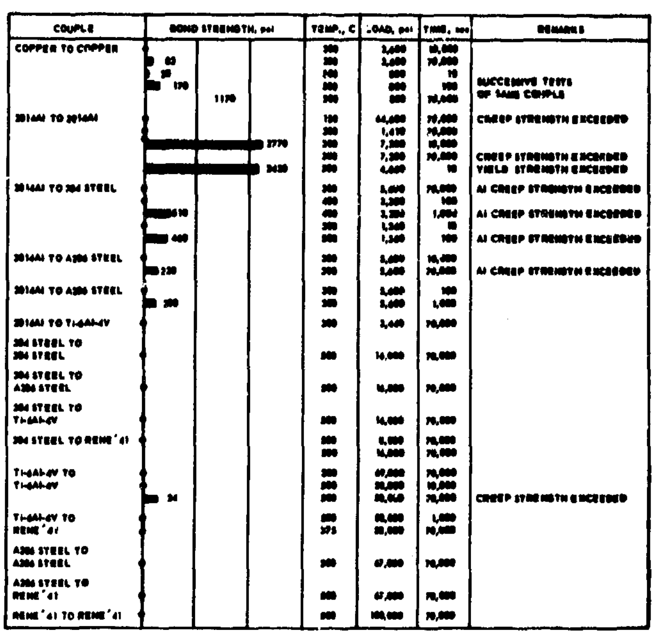

FIGURE 3. SUMMARY OF ADHESION AND COHESION TESTS(2)

For all materials except 2014 aluminum, the loads were based on 80 percent of the compressive yield strength of the material at temperature. Loads for aluminum were varied in an attempt to arrive at lo‿'s which would give negligible creep.

TABLE 1. TEST COUPLES(3)

(1)	OFHC copper (annealed) versus OFHC copper (annealed)
(2)	AISI type 304 CRES (annealed) versus AISI type 304 CRES (annealed)
(3)	2014 T-6 aluminum versis 2014 T-6 aluminum
(4)	2014 T-6 aluminum versus AISI type 304 CRES (annealed)
(5)	René 41 (solution treated and aged) versus René 41 (solution treated and aged)
(6)	René 41 (solution treated and aged) versus 2014 T-6 aluminum
(7)	René 41 (solution treated and aged) versus AISI type 304 CRES (annealed)
(8)	A286 steel (precipitation hardened) versus A286 steel (precipitation hardened)
(9)	A286 steel (precipitation hardened) versus 2014 T-6 aluminum
(10)	Ti-6Al-4V alloy (precipitation hardened) versus Ti-6Al-4V alloy (precipitation hardened)
(11)	Ti-6Al-4V alloy (precipitation hardened) versus 2014 T-6 aluminum
(12)	A286 steel (precipitation hardened) versus AISI type 304 CRES (annealed)
(13)	A286 steel (precipitation hardened) versus René 41 (solution treated and aged)

The relative ease with which the couples bonded in dynamic tests readily demonstrated how the mechanical abrasion denuded the surfaces of various films which prevent bonding.

The tests or procedures used for static loading during the second year of the program were essentially the same as those used in the early part of the work except for changes in technique. Contacting loads were limited to the lowest value meeting one or more of the following criteria: (1) 80 percent of the compressive yield strength of the weaker material at test temperature, (2) a load at which no creep would occur, (3) 5000 psi. The temperatures used were 25, 150, 300, and 500 C, except for couples containing aluminum. The maximum temperature for aluminum was 300 C.

The specimen parts for dynamic loading were prepared in the same manner as the static-loaded specimens. The top specimen part was oscillated slightly at a rate of 3 cps for the required test duration time, while the lower specimen part was held stationary.

The results of the static tests are shown in Figure 4. The conditions under which adhesion or cohesion occurred in dynamic tests and the resultant bond strengths are shown in Figure 5. Figure 6 compares the test conditions of maximum severity that resulted in no bonding with the minimum test conditions that gave bonding. A comparison is made in Figure 7 of the static and dynamic test results in terms of temperature at which adhesion or cohesion may be expected.

COUPLE	BOND STRENGTH, PSI (1000, 2000)	TEST CONDITIONS TEMP, °C	LOAD, PSI	TIME, SEC	REMARKS
COPPER TO COPPER		150	5800	≤ 70,000	
		300	1800	≤ 10,000	
	160	300	1800	70,000	
	30	500	800	10	SUCCESSIVE TESTS OF SAME COUPLE
	170	500	800	100	
	1170	500	800	70,000	
2014Al TO 2014Al		150	64,800	≤ 70,000	CREEP STRENGTH EXCEEDED
		300	1410	≤ 70,000	
		300	2200	≤ 10,000	
	890	300	2950	70,000	
2014Al TO 304 STEEL		150	25,500	≤ 70,000	
		300	2940	≤ 10,000	
	458	300	2950	70,000	
2014Al TO A286 STEEL		150	20,300	≤ 70,000	
		300	3440	≤ 10,000	
	60	300	3150	10,000	
2014Al TO Ti-6Al-4V		150	25,500	≤ 70,000	
		300	3800	≤ 10,000	
	1796	300	4050	70,000	CREEP STRENGTH EXCEEDED
		300	3440	70,000	
2014Al TO RENE' 41		150	25,500	≤ 70,000	
		300	2500	≤ 10,000	
	1750	300	3220	70,000	
304 STEEL TO 304 STEEL		500	16,000	≤ 70,000	
304 STEEL TO A286 STEEL		500	16,000	≤ 70,000	
304 STEEL TO Ti-6Al-4V		500	16,000	≤ 70,000	
304 STEEL TO RENE' 41		500	16,000	≤ 70,000	
Ti-6Al-4V TO Ti-6Al-4V		150	80,900	≤ 70,000	
		300	60,000	≤ 70,000	
		500	29,000	≤ 70,000	CREEP STRENGTH EXCEEDED
Ti-6Al-4V TO RENE' 41		500	98,000	≤ 1000	
		375	98,000	≤ 70,000	
A286 STEEL TO A286 STEEL		500	67,000	≤ 70,000	
A286 STEEL TO RENE' 41		500	67,000	≤ 70,000	
RENE' 41 TO RENE' 41		500	100,000	≤ 70,000	
17-4PH STEEL TO 17-4PH STEEL		500	64,800	≤ 70,000	

FIGURE 4. SUMMARY OF STATIC ADHESION AND COHESION TESTS(3)

Certain anomalies are shown in the data for some of the material combinations in that adhesion was obtained at relatively low loads but not at higher loads. The explanation was that the shear forces acting on the bonded specimens during elastic relaxation cause bond failure upon release of the compressive load and thus rupture the bonds if they are weak. The magnitude of the shear forces was proportional to the applied loads. The shear forces were increased when two materials of dissimilar modulae of elasticity made up the test couple, because the material with the lower modulus underwent more elastic deformation than the other. Though these forces were modest, they could have disrupted bonds that were weak. If test conditions were sufficient to form a strong bond, it is not likely that the bonds would have been affected by these forces.

The bulk of the Hughes work on adhesion of metals in the space environment is summarized in a paper by Winslow and McIntyre given at the AIAA/ASME Seventh Structures and Materials Conference, Cocoa Beach, Florida, April 18-20, 1966.(26)

SOLID-STATE ADHESION OF METAL STUDY AT NATIONAL RESEARCH CORPORATION

Studies on the solid-state adhesion of metals have been conducted at National Research Corporation for the past several years under the sponsorhip of NASA and the U. S. Air Force. Their work and that of Hughes complement each other.

The general objective has been to obtain additional information as to the conditions under which metals and alloys of engineering importance for space applications will adhere enough to hinder the relative motion or subsequent separation of components.

NRC, in addition to the preventive aspect of adhesion, has considered the cold-welding phenomenon in a more positive light: as a convenient and useful joining technique in space or vacuum. Metal-to-metal joints may exhibit important advantages such as an absence of a heat-affected zone surrounding the weldment. Also, dissimilar metals, which cannot be welded by conventional methods due to brittle phase formation or relative insolubility, can be joined by low-temperature adhesion techniques.

The following definitions are used in the NRC work: adhesion (cold welding) - the ability of two separate atoms, molecules, or materials to form a common bond; adhesion-coefficient (α) - the ratio of the force required to rupture the cold-welded bond and the force required to form the bond; compressibility factor (C) - the ratio of applied stress required to form the cold-welded bond, and the actual yield stress of the test material. In the case of dissimilar materials, the yield stress of the softest material was used.

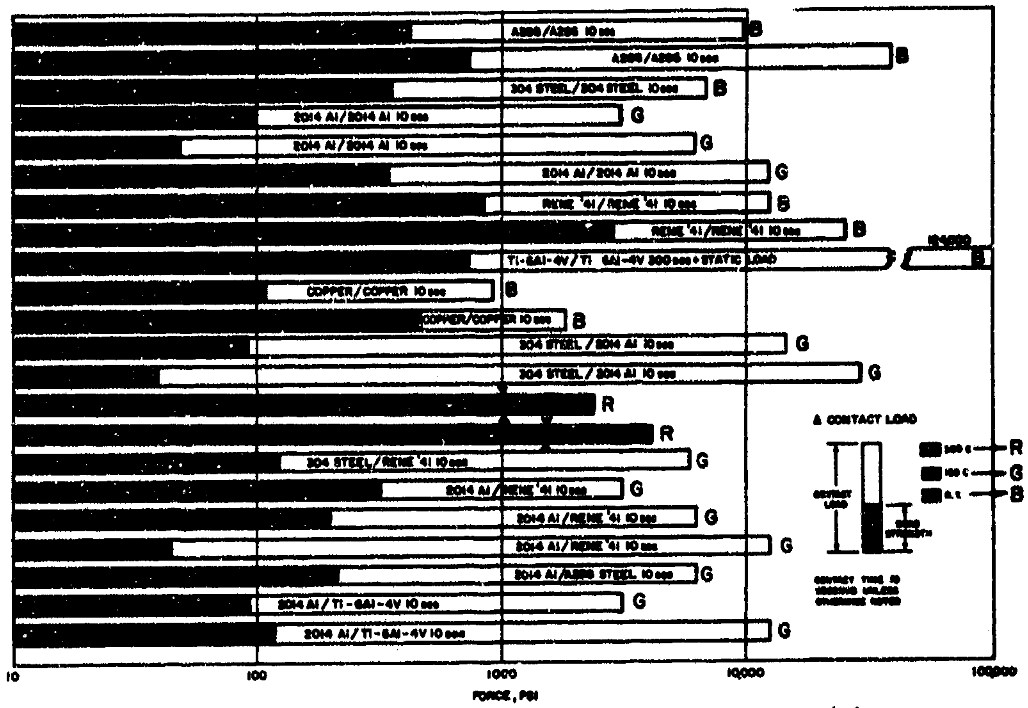

FIGURE 5. BOND STRENGTH OF COUPLES TESTED DYNAMICALLY(3)*

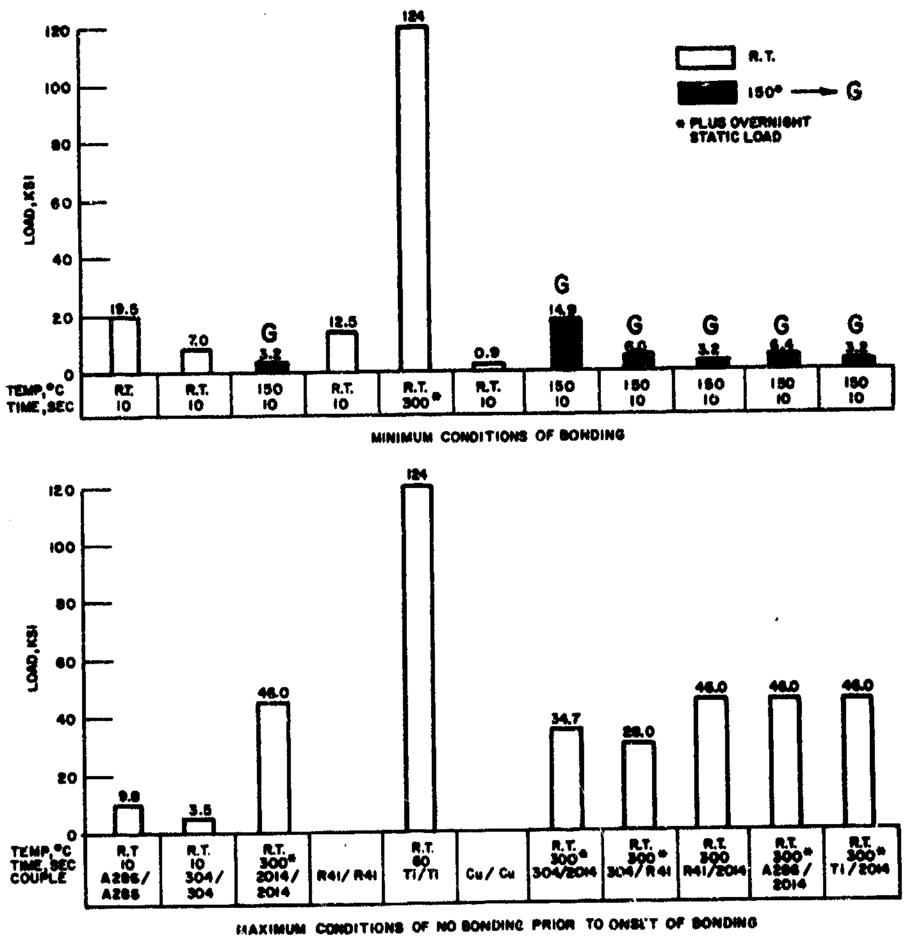

FIGURE 6. BONDING OF METALS UNDER DYNAMIC LOADING(3)*

* The bars in these graphs are colored. For clarification when reproduction occurs these letters are used: G = green, R = red, and B = black. The letters are at the top of the bar, they indicate temperatures.

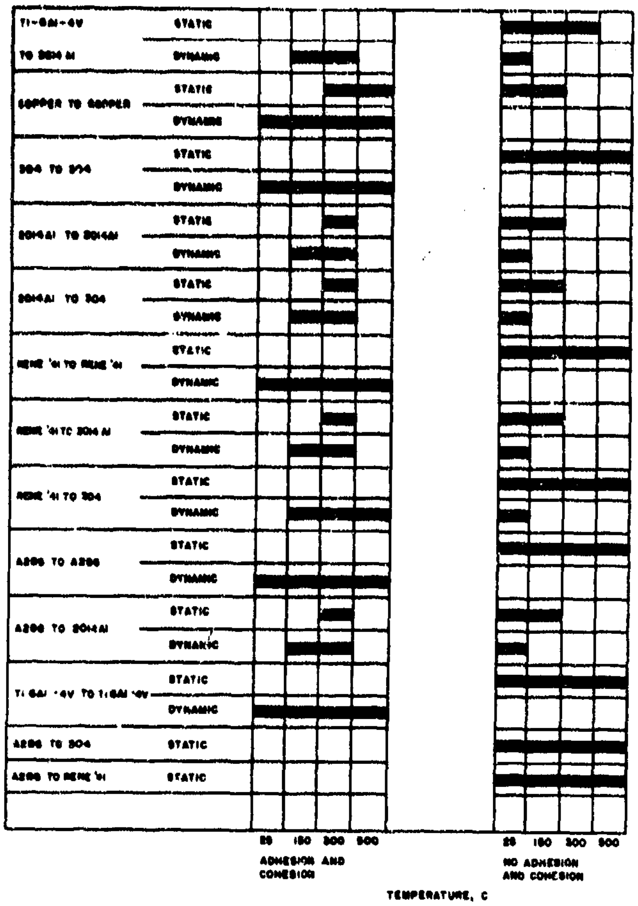

FIGURE 7. COMPARISON OF ADHESION AND COHESION UNDER STATIC AND DYNAMIC CONDITIONS AT VARIOUS TEMPERATURES(3)

These definitions are taken from a recent publication by NRC investigators and result from much work concerned with methods of interpreting the data selected.(4) Early reports (not all NRC research is covered by reports available at DMIC) contained much on the problem of the development of specimens, equipment, and technique.

A notched tensile-type specimen was used to evaluate cohesion at various temperatures by repeatedly fracturing and rejoining the specimen in a vacuum system capable of achieving pressures of 5×10^{-10} torr.(5) Actual pressures were always in excess of this, however, because of equipment outgassing. Copper, mild steel, and hardened steel were studied. The results were expressed in terms of percent cohesion; the ratio, average true cohesive stress to average true virgin fracture stress.

The effects of temperature in the range 25 to 500 C, environmental pressure, time the specimen components were apart, compressive stress, and the time the joint was in compression were evaluated. A make-and-break technique was used in this work.

The maximum cohesion obtained at room temperature was about 65 percent for OFHC copper, 19 percent for 1018 steel, and 0 percent for hardened 52100 steel. Time in contact appeared to be an important factor for copper at 200 C and above.

Both 1018 steel and 52100 steel were "self-cleaning" at 500 C, the former showing repeated readings near 100 percent cohesion, and the latter increasing in percent cohesion with each successive break. Except for steel at 500 C and copper at 350 and 400 C, cohesion dropped with each successive break. This was attributed to work hardening, with contamination contributing also when exposure was severe.

In follow-on research, the equipment used to join single notch-test tensile specimens was altered to permit eight tests during one pump-down of the vacuum system.(6) The specimen was also changed. Flat-face and chisel-edge shaped parts were used; the rectangular flat faces or the chisel edges were crossed during contact. The tests were run at room temperature and at pressures between 10^{-8} and 10^{-9} torr. Both similar and dissimilar combinations of the following metals at two hardness levels were studied; copper-beryllium alloy 1018 steel, 4140 steel, 440C steel, and titanium. The cleaning method used was wire brushing. Some development of a second method of cleaning, ion bombardment, was also begun during this period.

Conclusions drawn at that time (November, 1963), by NRC were as follows: (1) soft copper has no tendency to adhere to itself or to steel, titanium, or copper-beryllium alloy at 10^{-9} torr at room temperature after exposure to a pressure of 10^{-6} torr at 250 C, even when severely deformed in compression; (2) wire brushing at 10^{-9} torr after heating to 250 C at 10^{-6} torr can cause at least 6 percent cohesion between flat surfaces of soft copper, but not of soft steels at room temperature when slightly deformed in compression; (3) wire brushing of soft copper at 10^{-9} torr after heating to 250 C at 10^{-6} torr does not cause it to adhere to unbrushed steel, copper, titanium, or copper-beryllium alloy at room temperature after slight deformation in compression; (4) no cohesion occurs between specimens of soft steel or of soft titanium when severely deformed in compression between 10^{-9} torr after exposure at 10^{-6} torr at 250 C; and (5) much less cohesion occurs between pieces of soft copper after wire brushing in vacuum than after fracturing and rejoining in vacuum.

The most recent NRC reports available to DMIC cover research for Edwards Air Force Base under Contract No. AF 04(611)-9717.(7) It is concerned with the extent to which adhesion occurs between bare metal surfaces and the effectiveness of certain antiadhesion coatings. The materials studied ranged from very soft to very hard, and the coatings ranged from soft laminar films to hard oxide surface layers. The temperature range over which the adhesion properties were investigated was from 90 to 260 C. The stress levels used were from 0 to 1000 psi. The pressure under which adhesion measurements were made ranged from 760 torr to less than 10^{-13} torr.

The specimens for this program were fabricated from the following materials: OFHC copper, 2014-0 Al, stainless steel 17-4PH, stainless steel 440C, and tungsten carbide. The specimen shape and size is given in Figures 8 and 9. The faces of the specimen disks were the actual adhesion test surfaces. A specimen set consisted of one rotating specimen constrained between two similar fixed specimens. The method of assembling and the testing apparatus is adequately illustrated in the report.

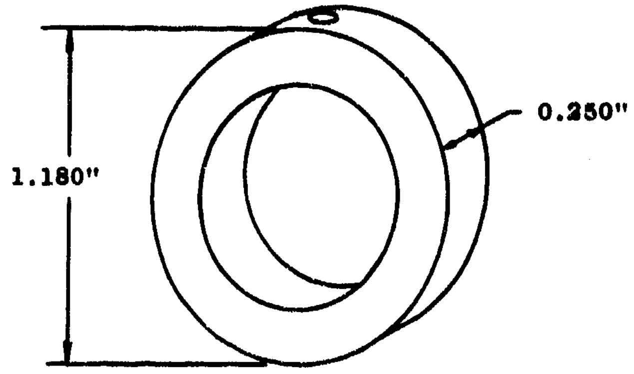

FIGURE 8. FIXED-POSITION TEST SPECIMEN(7)

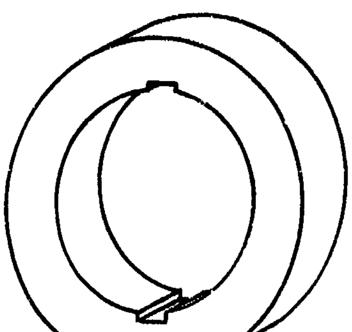

FIGURE 9. ROTATING TEST SPECIMEN(7)

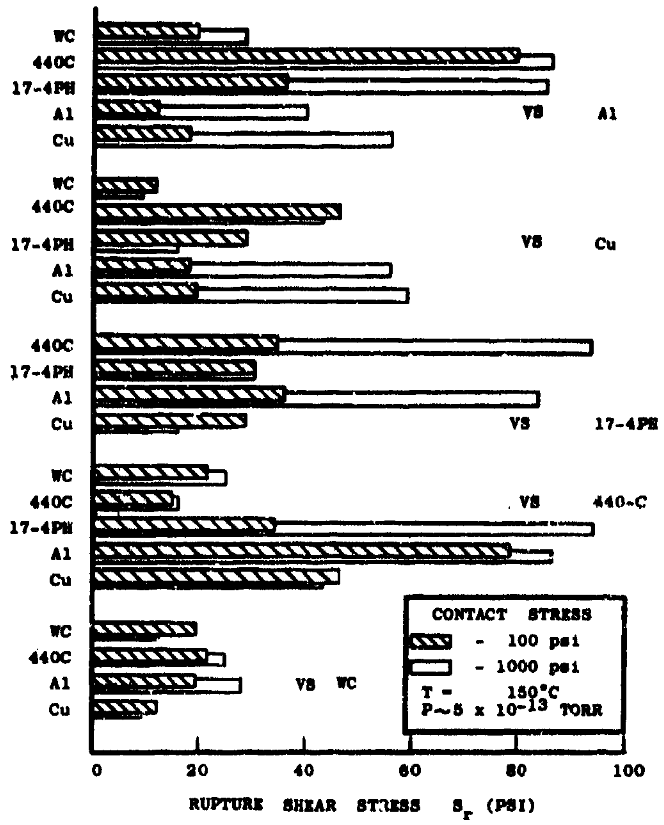

FIGURE 10. ROTATIONAL STRESS TO SHEAR RESIDUAL COLD WELDING AFTER RELEASE OF CONTACT STRESS FOR VARIOUS MATERIAL COMBINATIONS IN VACUUM(7)

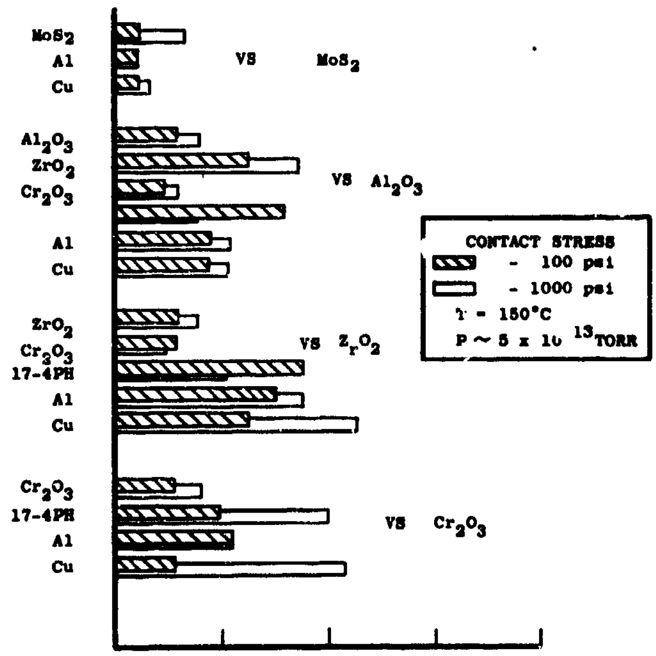

FIGURE 11. ROTATIONAL STRESS TO SHEAR RESIDUAL COLD WELDING AFTER RELEASE OF LOAD FOR COATED MATERIALS(7)

The metals were tested bare and with the following antiadhesion coatings: aluminum oxide, chromium oxide, zirconium oxide, and molybdenum disulfide. The oxide coatings were applied by the "Rokide" process. The coatings averaged 0.015 inch thick. The molybdenum disulfide was applied by the "electrofilm" process. The film thickness averaged about 0.0003 inch.

The bare metal specimen test faces were ground, polished, and lightly liquid-honed, using 325-mesh aluminum oxide to assure uniform surface conditions. The oxide-coated specimens were finished on 2/0 metallurgical polishing paper. The molybdenum disulfide coatings were applied to specimens that had been finished as described and received no further finish processing.

Specimens were cleaned by ultrasonic scrubbing in a detergent solution, acetone, and ethyl alcohol, prior to each series of experiments, and degassed before testing.

The experimental procedures used are too complex to detail here. The contacting surfaces were not rotated significantly under load until they had been at test temperature and under test load for 30 minutes. This was done to check for adhesion and to get a measure of the friction component of the shear stress to rotate. The results of this study are shown in Figures 10 and 11.

This report also contains a review of existing cold-welding studies and a set of design criteria developed to aid in preventing welding.

Based on the results of this program and the review, several interrelated parameters appear particularly important in controlling the welding process. They are: (1) surface cleanliness, (2) plastic stress-strain at the contacting interface, (3) mechanical properties (elastic modulus, yield strength, hardness, and ductility), (4) test temperature, (5) lattice structure, (6) surface-contour profile, (7) relative surface motion, and (8) vacuum environment.

Studies of the effects of these parameters on the cold-welding process may be utilized in formulating useful guides to minimize deleterious metal-metal bonding. The following points will be useful in preventing or minimizing the danger of cold welding: (1) Use high-modulus hard materials with limited ductility. (2) Maintain nonmetallic lubricant film such as MoS_2 between the contacting surfaces. (3) Avoid abrasive motion such as sliding, which might remove oxide or contaminant films. (4) Avoid contact stresses near yield stress of the softer materials; contact stresses should be as low as possible. (5) Avoid operating temperatures that exceed one-half the absolute melting point.

Also included in this report as a result of the review is a tabulation of data from several sources on solid-state welding in vacuum. In some cases, results reported in this table were standardized for comparability with other investigations. The table is reproduced in its entirety as Table 2.

Finally, NRC has examined the effect of lattice solubility as a mechanism important to cold welding.[4] Dissimilar-metal specimens made from metals that were completely soluble in each other at low temperature (copper-gold, copper-nickel, silver-gold, and columbium-tin) and from metals with less than 0.1 percent solubility at room temperature (copper-tin, silver-beryllium, silver-nickel, and gold-lead) were tested. The results shown in Figure 12 indicate that adhesion was obtained for both solubility conditions. As in previous work, the degree of cleaning, temperature, and loading were the prime test variables. The fourth variable was also evident from the results shown in Figure 12. This variable was that adhesion or cold welding was related inversely to the hardness (average yield stress) of the material pair.

STUDIES AT MIDWEST RESEARCH INSTITUTE

Another program concerned with the welding of metals when exposed to space environments was recently completed at Midwest Research Institute for NASA-Manned Spacecraft Center.[8] The approach used was to determine the coefficients of friction for various metal combinations under specified conditions and to relate these data to the likelihood of adhesion occurring.

The test apparatus used the concept of three pellets resting, or being rotated, on an annular wear track 2.3 in. in diameter. The three pellets, 0.065 in. in diameter, were rigidly mounted in a holder and supported a 9.2-pound weight; this weight produced a 1000-psi contact pressure between the pellets and the wear surface (based on projected area). Heaters were incorporated for maintaining the wear surfaces at approximately 200 C. Measurement of the force necessary to rotate the pellets gave the coefficient of friction. The mechanism was enclosed in a vacuum system capable of maintaining pressure in the 10^{-9} and 10^{-10} torr region.

The degree of cold welding was determined under static and dynamic conditions for 45 metal combinations in the high-vacuum environment. The metals investigated were: 2014-T6 aluminum, Ti-6Al-4V titanium alloy, Be-Cu, electrolytic grade cobalt, 321 stainless steel, Rene' 41, E-52100 steel, and coin silver. Each of the nine metals was tested against themselves and each of the other metals. The pellets were exposed to chamber pressure of less than 5×10^{-10} torr before contact was made, but during testing the chamber was in the 10^{-9} torr range. A static test consisted of a coefficient of friction being measured at breakaway after stationary contact of 300 hr, at a temperature of 200 C. The dynamic tests proceeded at a rotational velocity of 0.4 in./sec immediately after breakaway; it continued until the coefficient of friction exceeded 4.9 (limit of the test apparatus), the pellets wore excessively, or the time exceeded 100 hr.

The results of the investigations were compiled in several forms: (1) a ranking of the 45 metal combinations in order of increasing static coefficients of friction, (2) a similar ranking of the dynamic coefficients of friction during short-time testing, and (3) a tabulation of the coefficients of friction in a more convenient listing so that data of a particular metal combination could be readily located.

Table 3 is a ranking of the metals based on average coefficients of friction and gives the general tendencies of various metals to cold weld.

The static and dynamic coefficients of friction are presented in Figure 13 in a more convenient form for easier access to the design engineer. It includes the maximum and minimum values of the dynamic coefficients of friction as well as additional data for medium and long-time dynamic testing. Thus, the design engineer can locate the results of studies for a particular metal combination that he may be considering in a design problem.

The most interesting conclusion drawn by these investigators was that very little correlation existed between the coefficients of friction (or tendency to cold weld) and properties of the materials investigated.

Midwest also made a literature survey on the subject of cold welding in a vacuum. The material found is discussed in detail, and summaries of various investigations are tabulated.

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Cold welding in a high vacuum is of interest in the USSR, probably for the same reasons as in this country. The seizing of pure similar and dissimilar metals in a vacuum of 10^{-9} to 10^{-10} torr was investigated by Golego at room temperature at a rate of relative motion of the contacting surfaces of 1 mm/sec or under static pressure.[9] Thirty pure metals were tested under a stress of 5 percent of the tensile strength of the metal. It was found that with friction, under conditions of high vacuum all similar metals were susceptible to seizing. The coefficient of friction for dissimilar metals varied from 0.8 to 6.5 and depended on the

TABLE 2. SELECTED EXPERIMENTAL DATA ON ADHESION[7]

Material Combination	Bonding Pressure or Percent Plastic Deformation	Pressure	Temperature	Type of Test	Surface Preparation	Coefficient of Adhesion or Bond Strength	Investigator	Comments
Cu-Cu	60 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1	Vaidyanath, et al (1959)	—
Al-Al	60 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1	Vaidyanath, et al (1959)	—
Zn-Zn	70 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1	Vaidyanath, et al (1959)	—
Pb-Pb	60 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	0.9	Vaidyanath, et al (1959)	—
Sn-Sn	60 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1.0	Vaidyanath, et al (1959)	—
Al-Al	16 percent reduction in thickness	1 atmosphere (air)	600 C	Roll bonding	Degrease followed by wire brushing	0.5	Nicholas and Milner (1961)	—
Al-Al	16 percent reduction in thickness	1 atmosphere (air)	400 C	Roll bonding	Degrease followed by wire brushing	0.5	Nicholas and Milner (1961)	—
Al-Al	25 percent reduction in thickness	1 atmosphere (air)	300 C	Roll bonding	Degrease followed by wire brushing	0.5	Nicholas and Milner (1961)	—
Al-Al	40 percent reduction in thickness	1 atmosphere (air)	200 C	Roll bonding	Degrease followed by wire brushing	0.5	Nicholas and Milner (1961)	—
Cu-Al	70 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	14,000 psi	McEwan and Milner (1962)	—
Cu-Fe	70 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	24,000 psi	McEwan and Milner (1962)	—
Cu-Ni	70 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	24,000 psi	McEwan and Milner (1962)	—
Cu-Ag	70 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	22,000 psi	McEwan and Milner	—
Cd-Fe	59 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	4,200 psi	McEwan and Milner (1962)	Insoluble pair
Fe-Pb	59 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1,800 psi	McEwan and Milner (1962)	Insoluble pair
Cu-Pb	57 percent reduction in thickness	1 atmosphere (air)	RT	Roll bonding	Degrease followed by wire brushing	1,600 psi	McEwan and Milner (1962)	Insoluble pair
Cu-Mo	54 percent reduction in thickness	1 atmosphere (air)	600 C	Roll bonding	Degrease followed by wire brushing	10,000 psi	McEwan and Milner (1962)	Insoluble pair
Cu-Mo	58 percent reduction in thickness	1 atmosphere (air)	900 C	Roll bonding	Degrease followed by wire brushing	18,000 psi	McEwan and Milner (1962)	Insoluble pair
Fe-Al	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	Sticking observed	Keller (1964)	Soluble pair
Cu-Ag	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	Sticking observed	Keller (1964)	Soluble pair
Ni-Cu	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	Sticking observed	Keller (1964)	Soluble pair
Ni-Mo	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	Sticking observed	Keller (1964)	Soluble pair
Cu-Mo	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombard0	No sticking	Keller (1964)	Insoluble pair
Ag-Mo	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	No sticking	Keller (1964)	Insoluble pair
Ni-Cu	Touch contact	10^{-11} torr	RT	Hemisphere on flat	Argon ion bombardment	No sticking	Keller (1964)	Insoluble pair
Ni-Mo	Touch contact	10^{-11} torr	RT	Hemisphere	Argon ion bombardment	No sticking	Keller (1964)	Insoluble pair
Cu-Cu	90 percent	10^{-8} torr	RT	Rupture and rejoin	None	0.65	Ham (1963)	Used a notched tensile spec
Cu-Cu	20 percent	10^{-8} torr	RT	Rupture and rejoin	None	0.29	Ham (1963)	Used a notched tensile spec
Cu-Cu	10 percent	10^{-8} torr	RT	Rupture and rejoin	None	0.07	Ham (1963)	Used a notched tensile spec
1020-1020 steel	150 percent	10^{-8} torr	500 C	Rupture and rejoin	None	1.0	Ham (1963)	Used a notched tensile spec
1020-1020 steel	0 percent	10^{-8} torr	500 C	Rupture and rejoin	None	0.92	Ham (1963)	Used a notched tensile spec
Pb-Pb, Al-Al, Au-Au, Ag-Ag	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in tension	Filed by hand	5.0 to 7.0	Sikorski (1964)	Maximum coefficient of adhesion measured in repeat tests
Cu-Cu	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in tension	Filed by hand	12	Sikorski (1964)	—
Pd-Pd	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in tension	Filed by hand	17	Sikorski (1964)	—

TABLE 2. (continued)

Material Combination	Bonding Pressure or Percent Plastic Deformation	Pressure	Temperature	Type of Test	Surface Preparation	Coefficient of Adhesion or Bond Strength	Investigator	Comments
Rare earths except Yb and Ce	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in tension	Filed by hand	0.02 to 0.35	Sikorski (1964)	All are HCP structure
Yb-Yb	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in tension	Filed by hand	3 to 4	Sikorski (1964)	—
Ce-Ce	200 to 1000 psi	1 atmosphere (air)	RT	1/4 in. diameter rods pressed end to end and rotated 180° under load, pulled in	Filed by hand	0.7	Sikorski (1964)	—
Cu Cu (soft)	30,000 psi	$3-6 \times 10^{-9}$ torr	125 C	Compression of crossed anvils	None	0	National Research Corp.	Unpublished data
Cu-Cu (soft)	30,000 psi	$3-6 \times 10^{-9}$ torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 1/2 min	0.12	National Research Corp	Unpublished data
Cu-Cu (soft)	30,000 psi	$3-6 \times 10^{-9}$ torr	100 C	Compression of crossed anvils	Wire brushed in vacuum 5 min	0.45	National Research Corp	Unpublished data
Cu-Cu (hard)	30,000 psi	$3-6 \times 10^{-9}$ torr	100 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0.125	National Research Corp	Unpublished data
1018 steel-1018 steel	33,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0	National Research Corp	Unpublished data
440C-440C	33,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0	National Research Corp	Unpublished data
Pure Al-Pure Al (soft)	35,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0.16	National Research Corp	Unpublished data
CuBe-CuBe	33,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0	National Research Corp	Unpublished data
Ti-Ti	52,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0	National Research Corp	Unpublished data
Cu-Ti	33,000 psi	4×10^{-9} torr	130 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0.04	National Research Corp	Unpublished data
Cu-Al	33,000 psi	4×10^{-9} torr	130 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0.40	National Research Corp	Unpublished data
Cu-CuBe	48,000 psi	4×10^{-9} torr	130 C	Compression of crossed anvils	Wire brushed in vacuum 3 min	0.20	National Research Corp	Unpublished data
Cu-1018 steel	44,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 2 min	0.15	National Research Corp	Unpublished data
Cu-4140 steel	71,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 2 min	0.02	National Research Corp	Unpublished data
Cu-440C	83,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 2 min	0.02	National Research Corp	Unpublished data
6061Al-6061Al (hard)	15,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 2 min	0.02	National Research Corp	Unpublished data
2024Al-2024Al (hard)	15,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 2 min	0 - 0.03	National Research Corp	Unpublished data
Au-Au (soft)	27,000 psi	4×10^{-9} gorr	125 C	Compression of crossed anvils	No cleaning	0	National Research Corp	Unpublished data
Au-Au (soft)	24,000 psi	4×10^{-9} torr	125 C	Compression of crossed anvils	Wire brushed in vacuum 1/2 min	0.17	National Research Corp	Unpublished data

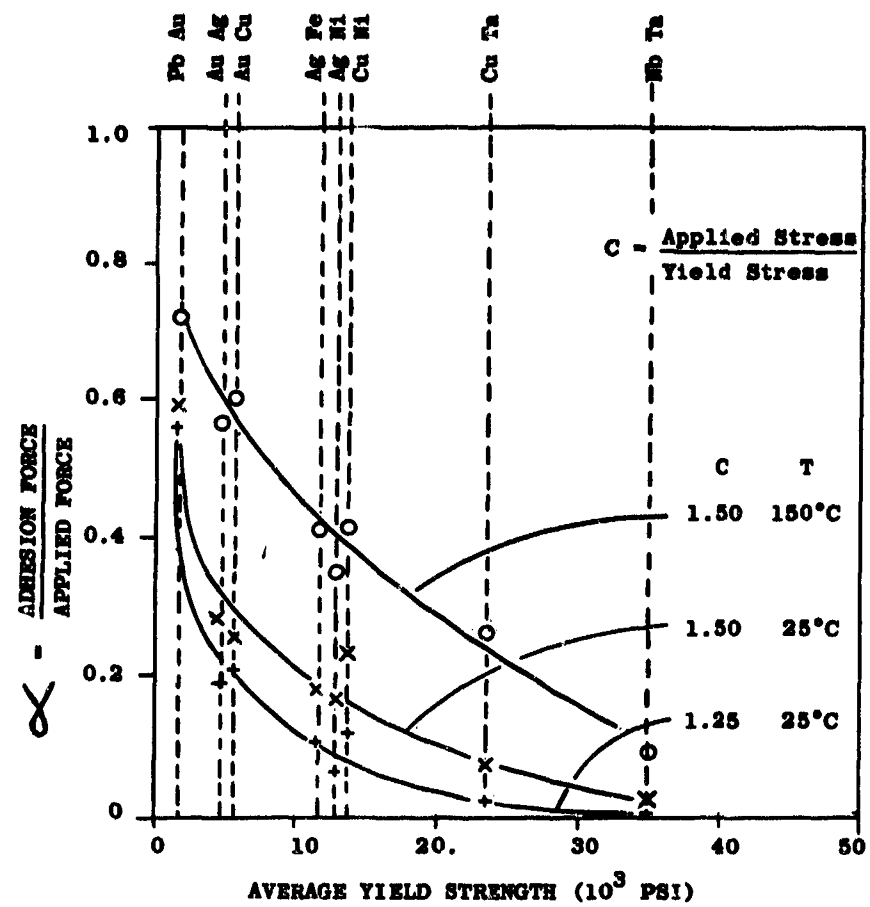


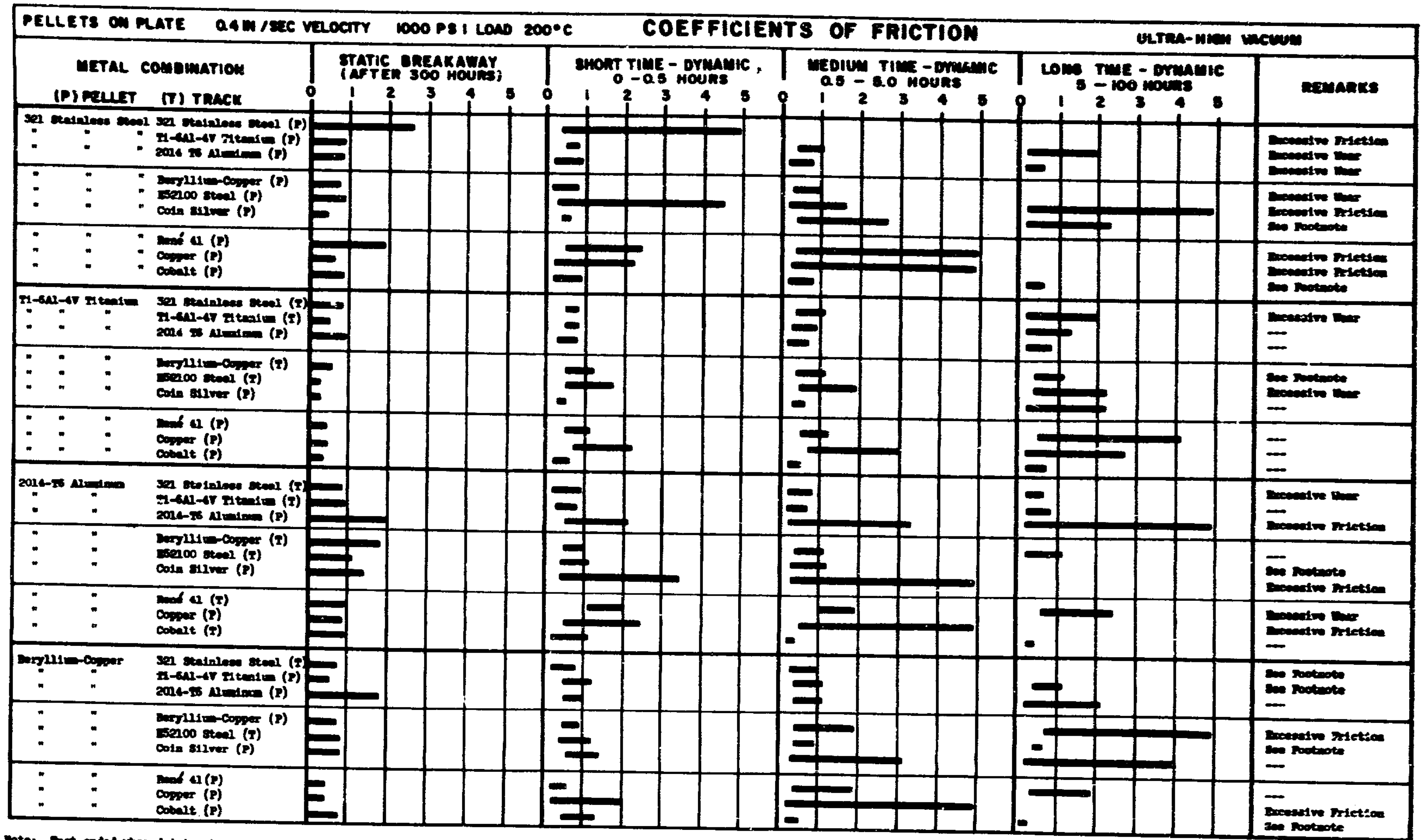
FIGURE 12. ADEHSION COEFFICIENT AS A FUNCTION IN YIELD STRESS FOR VARIOUS SAMPLE MATERIALS(4)

TABLE 3. RANKING OF THE TENDENCY OF METALS TO COLD WELD IN ULTRAHIGH VACUUM AVERAGE COEFFICIENTS OF FRICTION(8)

Static Breakaway,(a) after 300-hr soak		Dynamic Coefficient,(a) maximum value	
Ti-6Al-4V titanium	0.46	Cobalt	1.43
Beryllium-copper	0.81	Ti-6Al-4V titanium	1.59
321 Stainless steel	0.86	Beryllium-copper	2.36
René 41	0.86	2014-T6 aluminum	2.52
Cobalt	0.89	321 Stainless steel	2.53
Coin silver	0.92	E52100 steel	2.86
Copper	1.03	Coin silver	3.40
E52100 steel	1.06	René 41	3.63
2014-T6 aluminum	1.21	Copper	3.80

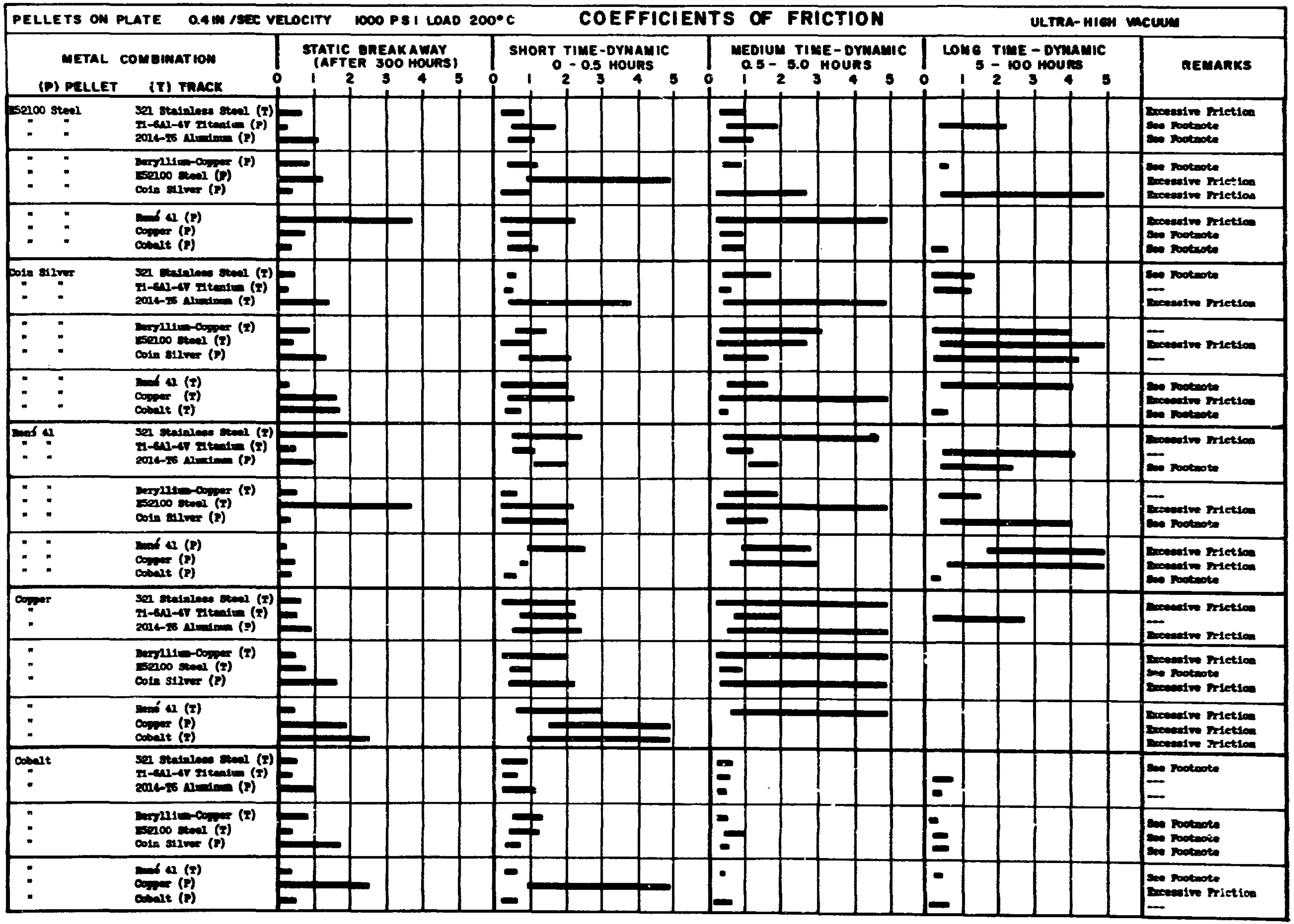
(a) Average values from metal combinations of specified metal with itself and the eight other metals.

Note: This table is based only on the average coefficients of friction under the one set of parameters: controlled surface finish and flatness, specimen temperature 200 C, contact pressure 1,000 psi, chamber pressure less than 5 x 10^{-9} torr, and rotational velocity of 0.4 in. sec for the dynamic tests.



Note: Test ended when driving torque and sound decreased significantly, indicating loss of contact between test surfaces.

Data from single run with each metal combination.



Note: Test ended when driving torque and sound decreased significantly, indicating loss of contact between test surfaces.

Data from single run with each metal combination.

FIGURE 13. TABULATION OF COEFFICIENTS OF FRICTION FOR ALL METAL COMBINATIONS

mechanical strength of the metals and the load and intensity of seizing. (This conflicts with the conclusion reached by Midwest investigators) The mutual solubility of metals had no effect on the initiation and development of the process of seizing. (This agrees with NRC results) For example, iron-chromium, iron-aluminum, and iron-titanium pairs (the room-temperature solubility of chromium, aluminum, and titanium in iron is 100, 32, and 3 percent, respectively), experienced seizing with friction. No seizing was observed in iron-antimony and iron-zirconium pairs, although both metals are soluble in iron (antimony 7 percent, zirconium 0.15 percent). Iron-scandium and iron-magnesium pairs experienced no seizing. Neither scandium nor magnesium are soluble in iron. Two other pairs with mutually insoluble components, iron-silver and copper-molybdenum, experienced partial seizing. The difference in crystal lattice structure also had no effect on seizing. Only differences in atomic diameters were found to have considerable effect. Intensive seizing was observed between metals with atomic diameters differing by 15-18 percent, but no seizing occurred when the difference was larger.

FUNDAMENTAL STUDIES

Keller and his co-investigators at Syracuse University have been studying the fundamental aspects of metal-metal adhesion for a number of years.[10-12] They have been concerned with the broad basic concepts such as the crystallographic orientation of contacting pure metals. Much of their research is directed toward the confirmation of the theoretical concepts developed. The practical data are presented in Table 4.

TABLE 4. SUMMARY OF INVESTIGATIONS BY KELLER

Materials	Iron-aluminum Silver-copper Nickel-copper Nickel-molybdenum Copper-molybdenum Silver-molybdenum Silver-iron Silver-nickel Germanium-germanium
Vacuum Range	2×10^{-11} torr
Temperature Range	Room temperature
Load Range	Very small
Adhered or Cohered Pairs	Iron-aluminum Silver-copper Nickel-copper Nickel-molybdenum
Nonadhered or Noncohered Pairs	Copper-molybdenum Silver-molybdenum Silver-iron Silver-nickel Iron-germanium-iron (10^{-8} torr)
Comments	Specimens cleaned by vacuum exposure and argon ion bombardment. Numerical data not given.

There are, in both the open literature and Government reports, numerous publications that cover the fundamentals of adhesion and cohesion of metals, as studied by Bowden and others. Data from these studies will not be included here because they are not of direct value to the designer who requires engineering data on standard materials of construction. It does seem appropriate, however, to include some coverage of earlier work that is relevant to space cold-welding problems. A short review of this early work was made by Midwest Research Institute investigators. The following paragraphs were taken from their report.[8]

"The friction of clean surfaces was studied by Bowden and Hughes in 1939,[13] at pressures of 10^{-6} torr; the adsorbed film of oxygen and other contaminants were removed from the test surfaces by ion bombardment. Immediately upon cooling, the coefficient of friction for nickel on tungsten and copper on copper were between 4.5 and 6. When a trace of oxygen was admitted the coefficient dropped to 1 or less, while pure hydrogen or pure nitrogen had little effect on the friction of clean metal surfaces. Bowden and Young[14] subsequently conducted the same experiment but with improvements so that the slider could be dragged along the fixed surface and with higher loads, about 15 grams instead of less than 1 gram. Degassing and surface cleaning was accomplished by heating in vacuum to 1000 C by induction. Their results confirmed the earlier work. They support the view that surface oxides and other contaminants prevent the formation of metallic junctions at the interface which would occur with clean surfaces because of cold welding. Bowden and Rowe[15] in the same general type of investigation measured adhesion forces in addition to frictional forces. They were concerned with the adhesion between hard metal surfaces cleaned by heating at pressures of 10^{-6} torr, and later, 10^{-8} torr. The hard metals had low adhesion values even for clean surfaces; the low values were attributed to the plastic recovery of these surfaces upon removal of the load as had been earlier reported. Contamination was found not to be an important factor in adhesion for pure normal loading. However, adhesion was increased significantly if a tangential load was applied to cause a growth of the real contact area; contamination became a large factor in this latter case. When the metals were heated in vacuum to temperatures high enough to anneal the asperities of the surfaces, very large adhesions were recorded for pure normal loading."

"Theoretical and experimental studies of mechanisms of metallic friction, friction and surface damage of sliding metals, area of contact between solids, effects of contaminant films on friction of clean surfaces and other related topics prior to 1953 were described by Bowden and Tabor;[16] a continuation of various investigations to 1963 was given in their subsequent volume.[17] Much of their discussion is pertinent to cold welding studies."

"The works of Anderson,[18-20] was largely intended to experimentally test the adhesion theory of friction both by Bowden and Brown, and to develop methods for thermal compression bonds of wire leads to brittle metals. They showed the effects of shear strains in the structure of metal surfaces and substrates after adhesion. These shear strains are generally necessary for adhesions as they are very effective in removing surface oxides; they roughen the surface, increase the amount of atomic contact, and produce a work-hardened zone near the common interface, all of which increase the adhesion strength of the joint."

"The investigations of Burton, Russel, and Ku[21] were concerned with static dynamic coefficients of friction of metal surfaces cleaned by hydrogen bake-out and other means at temperatures of -250 to + 25 C. A spherical radius was rubbed on internal surfaces of a cylinder in a helium atmosphere. The coefficients had virtually no change throughout the temperature range. Later, the same authors[22] studied friction of lead-plated tool steels and effects of oxide coatings on copper under the same conditions. Burton, Brown, and Ku[23,24] conducted friction and wear characteristics of oscillating, plain journal, and self-aligning bearings over the range -90 to 1750 F at pressures ranging from 10^{-6} to 10^{-3} torr. They studied cermets and high-temperature metal alloys with the test surfaces subjected to rotating motion under normal loading from 1500 to 15,000 psi and at temperatures up to 2000 F. The tendency toward adhesion, gross seizure, and severe surface roughening was much less for the cermets than for the metal alloys."

DISCUSSION

The available literature on that portion of space-environmental technology concerned with the welding of metals used for construction of space hardware is summarized here. It is apparent that practical information that is concerned with these materials is not plentiful. The reasons for this seem to be numerous.

A very large portion of the research conducted so far has been directed toward learning the fundamentals involved. As a result, there appears to be a good understanding of the fundamentals such as surface conditions, temperature, and physical properties. This basic information now needs to be applied to those alloys that are useful to the designer.

Investigations are all influenced by the mechanics of simulating space environments and in maintaining them for significant lengths of time. Much progress has been made in this area; it may be time for those interested to consider standardization of both the methods of space simulation and test specimens. Programs in progress will assist in the choice of the most useful methods through comparison with actual in-space studies.

Solution of the problems of lubrication of moving parts in a space environment has taken precedence over direct studies concerned with adhesion and cohesion. This is justifiable because of the urgency of the problem, but it has led to great interest in the prevention of welding, while the use of welding as a method of assembly has been of secondary interest.

There is a lot to be learned about the space-welding phenomenon and how it varies with materials, environmental conditions, time, temperature, etc. Until such information becomes available, more will be learned from actual space flights than from ground-based simulations. There is little doubt, however, that with careful consideration of the designs, probable events during flight, and utilization of knowledge now available, satisfactory operation can often be predicted. A good example of this was recently reported.[25] A gold-plated antenna on a research satellite was coiled in a retaining cup during launch. Vibration occurred during the prelaunch stage, which caused cold welding in the wear-cleaned areas after the device was in space. Subsequently, the welds were progressively broken due to thermal shock as the device orbited in and out of cold and hot areas. The result was that the antenna, which did not work well when placed in orbit, slowly improved over a period of several weeks - as the weld broke the antenna extended as intended. This explanation of the events was made by deduction, but the data were later verified in the laboratory. Utilization of existing data could have prevented the difficulty if the vibration had been anticipated.

The literature reviewed, the volume of work referenced in them, and the variety of material covered by the admittedly incomplete annotated bibliography appended show a need for comprehensive collection and correlation of space-welding literature. At least two organizations are working to accomplish this need. The ASTM recently organized Subcommittee 6 of the Materials Section VI, ASTM Committee E21 to be concerned with adhesion of materials in the space environment. They will collect and correlate significant data produced by various investigators in the field. A task was recently initiated at Battelle Memorial Institute by the Redstone Scientific Information Center to examine the state of the art on cold welding of electrical connections in space. Battelle will cover all available information at least as far back as 1960. Both methods of accomplishing and preventing welding of selected metal surfaces in high and ultrahigh vaccum (10^{-6} torr to 10^{-13} torr or better) will be included in their report.

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   Announcement of the renewal of a contract for "Cold-Welding Studies" at The Franklin Institute, Philadelphia, Pennsylvania. Sponsored by the Office of Naval Research under Contract No. Nonr-4825(00). One report has been written in past work. The new program is to study and analyze atomic bonding phenomena and the properties of clean surfaces. Dr. Hans Conrad is the chief investigator.

2. Judge, J. F., "Cold Welding Promises Means to Bond Dissimilar Metals", Missiles and Rockets, 18 (14) 24 (April 4, 1966).
   Short, one-page summarization of past work at the National Research Corporation, Cambridge, Massachusetts.

3. McWithey, R. R., and Hayduk, R J., "Damping Characteristics of Built-Up Cantilever Beams in Vacuum Environment", Technical Note NASA TM D-3065, Langley Research Center, Langley Station, Hampton, Virginia (November, 1965).
   The amount of structural damping present in a built-up structure may be significantly altered if the environmental conditions to which the structure is subjected allows the phenomenon of cold welding to occur. Damping measurements were made on solid and built-up cantilever beams

in a vacuum environment to determine the effects of structural damping. The changes from damping characteristics were noted for various values of clamping pressure between beam laminates for the case of the built-up beams. Results indicated no significant changes in structural damping characteristics, as a result of exposure to pressure as low as 1×10^{-9} torr.

4. "ERS Valve Certification Test", Technical Report No. AFRPL-TR-65-84, Air Force Rocket Propulsion Laboratory, Edwards Air Force Base, California, (April, 1965).
Short report on studies made to determine the type of valve which will be used during an in-space investigation of cold welding of metallic interfaces. Small solenoid valves are to be used to provide these interfaces at the seat/poppet contact surface.

5. Jamison, W. E., "Feasibility Study of Techniques to Protect Mechanisms Operating in Space from Malfunction", Technical Summary Report K-6055 IIT Research Institute, Chicago, Illinois, (January, 1965).
A thesis is developed that abandons the classical friction interface for a new interface which is considered a volume which, in the ideal case, would contain a plane of zero shear strength. Consequently, current lubrication practices show little promise of meeting the anti-friction requirements for space applications.
The solution is the development of new materials and surfaces for the modification of old ones to provide the needed interfacial conditions. Recommendations are made on how to accomplish this and some experimental work directed toward that end is covered.

6. "Octahetral Research Satellite-Mark II for Cold-Welding Experiments", Quarterly Progress Report No. 4, TRW Space Technology Laboratories, Redondo Beach, California, Contract AF 04(611)-9883 (May 31, 1965).
This report covers the progress toward the development, fabrication, and delivery of a satellite for in-space experimentation. The basic experimental objective is to study the phenomena of cold welding as it applies to materials in valves of propulsion systems. The satellite system is designed for a sub-satellite launch operation where the satellite is carried as an auxilliary pay load on board a primary mission.

7. Bryant, E. J., Gosselin, C. M., and Longley, W. W., "Extreme Vacuum Technology Developments", Contractor Report, NASA CR-324, Midwest Research Institute, Kansas City, Missouri, Contract NASr-63(06) (November, 1965).
Several phases relating to the attainment, measurement, and application of ultra-high vacuum environments are reported. The phases covered are: development of a dual-expansion nozzle for vapor-jet studies; determination of the gases present in UHV systems with oil diffusion and getter-ion pumping; measurements and theory on cryopanel operation; establishment of cold-welding criteria; and determination of response characteristics for extreme high-vacuum gages and field emission microscopes. The lack of cold welding with touch contact of structural materials and the accomplishment of cold welding with vibrational contacts is discussed.

8. Kellogg, L. G., "Develepments in High-Temperature, Ultrahigh-Vacuum Friction Studies", Lubrication Engineer, 22 (2) 57-66 (February, 1966).
Experimental studies were conducted to determine what materials could be used to provide bearing compatibility on nuclear reactors in space. Screening tests were conducted on 67 material pairs in sliding couples at ultrahigh vacuum. The friction couples were categorized into 7 groups: metal versus metal, metal versus metal with brine lubricants, metal versus carbon, ceramic versus ceramic, ceramic versus ceramic with brine lubricants, metal versus ceramic, and ceramic versus carbon. Special tests were conducted using contaminant films with all groups.
Data are presented to illustrate the effects of vacuum on sliding friction and the effects of vacuum on surface film formation. Results indicated that carbon-graphites and sodium-silicate bonded brine-film lubricants provide relatively low friction in vacuo at 1000 F when coupled with flame-sprayed aluminum oxide surfaces.

9. Steinberg, S., and Roepke, W., "Investigation of Surface Energy States of Single-Crystal Metals", Report No. ARL64-25, General Mills, Incorporated, St. Paul, Minnesota, Contract AF 33(657)-8038 (February, 1964).
A high-vacuum system containing a unoplasmatron, friction-measuring equipment, and a contact potential difference determination device was developed. With this system, average coefficient of friction and contact potential difference measurements were made on copper single crystals oriented in the (100) and (111) planes, and iron single crystals oriented in the (110) plane, after exposure to ion bombardment for varying periods of time. The data show a trend toward an increase of coefficient of friction and contact potential difference with longer ion-beam exposures.

10. Ryan, J. A., "Experimental Investigation of Ultra-High Vacuum Adhesion as Related to the Lunar Surface", Second Quarterly Progress Report, Missile and Space Systems Division, Douglas Aircraft Company, Incorporated, Santa Monica, California, Contract NAS7-307 (June 26, 1964). (Report date questioned because time covered by quarterly report show October through December, 1964).
The purpose of the program was to obtain data relating to the possible behavior of silicates at the lunar surface and to determine the degree to which this behavior can pose problems to lunar surface operations. The approach used was to obtain quantitative data relating to silicate vacuum friction-adhesion through the use of "single crystal" samples of the various common silicate minerals. This approach could give a basic understanding of the physics of silicate behavior in vacuum. Work covered by available reports is not far enough along for real data accumulation.

11. Bryant, P. J., Gosselin, C. N., and Taylor, L. H., "Extreme Vacuum Technology (below 10^{-13} torr) and Associated Clean Surface Studies", Contractor Report NASA CR-884, Midwest Research Institute, Kansas City, Missouri, Contract No. NASr-63(06) (July, 1964).
Work covered is divided into five phases: (1) development of extreme vacuum technology utilizing a vapor-jet mechanism and a helium permeation-guard technique.[1] A helium-guard technique for glass was developed which lowers

the permeation of helium by three orders of magnitude. The technique consists of treatment with cesium metal. (2) Determination of the qualities and species of gas above getter-ion pumps and chemically trapped oil diffusion pumps. (3) Derivation of a physical adsorption isotherm for inert gases. (4) Development of a total-pressure gage for readings below 10^{-12} torr. (5) Investigation of the adhesion of metals exposed to vacuum and thermal out-gassing.

12. Howard, W. W., and Bauer, J. M., "Engine-operating Problems in Space, Volume I--The Experimental Program", Report No. NASA CR52044, Aerojet-General Corporation, Azuza, California (April, 1963).

The objective of the program was to define problems associated with the operation of liquid-propellant rocket engines in space. Environmental factors considered included nuclear radiation, vacuum, temperature extremes, micrometeoroids, ethylene oxide/Freon-12 sterilant, ammonia gas, methane gas, and dust.

A wide variety of accomplishments are summarized which cover the effect of environment on thrust chambers, solid-propellant gas generators, and other liquid-rocket components.

13. Chinn, J. L., "The Effects of Space Environment on Materials", North American Aviation, Incorporated, Downey, California, Report received September, 1963.

This paper is a general discussion of space environmental effects on materials, with particular emphasis on materials used in Apollo-type spacecraft. General coverage is given of the space environment and its effect on spacecraft materials while considerable detail is devoted to charged particle space radiation, its origin, and its effects on space materials.

14. Menard, R. C., and Anderson, A. A., "Investigation of Surface Energy Space of Single Crystal Metals", Report No. ARL-63-139, General Mills, Incorporated, St. Paul, Minnesota, Contract No. AF 33(657)-8038 (August, 1963).

An ion beam sputter cleaning apparatus was developed to operate in a high vacuum system. This apparatus, known as a uniplasmasmatron, creates positive ions from various gases and focuses them into a beam of controlled density and energy. Bombarding ion currents of 80 micro amps are obtained. Experiments show that this current is sufficient to produce large, smooth, brightly etched surfaces on copper specimens.

A contact potential device was also developed to study the surface energy of single-crystal metals in a vacuum.

15. Clauss, N. J., "Lubrication Under Space/Vacuum Conditions", Lockheed Aircraft Corporation, Sunnyvale, California, Report No. 5-10-62-47, Contract AF 04(647)-787 (October, 1962).

The effects of space environment on friction and wear, on the lubricants, and self-lubricating materials for spacecraft mechanisms were discussed.

Experimental studies demonstrated the feasibility of using selected oils and greases to lubricate highly loaded ball bearings without replenishment for periods of over one year under the following conditions of operation: speeds of 8000 rpm, temperatures of 160 to 200 F, and vacuum of 10^{-8} torr. Over one-half year of successful operation was achieved under similar operating conditions with self-lubricating retainers of reinforced Teflon, provided that the loads were light. Bonded films of molybdenum disulfide gave shorter lifetimes and poor reproducibility.

16. Gustafson, J. H., and Bentley, G. A., "Survey of Frictional Problems in Spacecraft", Final Report, Marlin-Rockwell Corporation, Jamestown, New York (February 16, 1962).

A survey of frictional problems in spacecraft mechanisms was conducted for the JPL in order to determine the degree of research and development effort which is required to solve the problems introduced by space environment.

Recommendations on materials choice are made, recognizing the pressures of the time schedule for space exporation. Recommendations for subsequent research and development are made to produce maximum results in a minimum length of time and in keeping with the increased complexity of future missions.

Appended to this report is a separate report on an extensive review of available literature on electrical contacts in space environment. It was concluded that the problems with contacts in space are but specific cases of general problems which have not yet been fully solved for operation on earth. Areas of needed research are pinpointed.

17. Menard, R. C., Anderson, A. A., and Roebke, W. W., "Investigation of Surface Phenomena With Electron Mirror Microscopy", Report No. ARL 62-333, General Mills Corporation, Minneapolis, Minnesota, Contract No. AF 33(616)-6178 (April, 1962).

The objectives of the program were to determine the feasibility of using the electron mirror microscope to study specialized surface phenomena and to use this instrument in conjunction with a light-load boundary friction apparatus to investigate the friction and durability characteristics of thin films on metal substrates.

Characteristics of thin surface films on titanium were studied with light-load friction experiments in a vacuum of 10^{-6} torr. Three surface types were used: "clean" titanium, oxide-coated titanium, and titanium coated with monolayers of polar organic compounds. The results are discussed in terms of current friction theory.

18. Bergman, N., and McCain, J. W., "Coefficient of Friction of Metals in a Vacuum", North American Aviation, Incorporated, Rocketdyne, Canoga Park, California, Report No. TANN-2114-622 (July 3, 1962).

Reference was made to a research program covering friction of metals in a vacuum of 10^{-5} to 10^{-6} torr. (see Reference A-24) A curve was published in the reference which gave the coefficient of friction of 19 metal combinations tested versus running time in both air and vacuum. It was indicated that friction was 60 percent more in vacuum than air, and further, that in both cases running friction rose about 50 percent over additional startup within 10 minutes, then tended to level off.

It appeared that this curve was very misleading because when each metal combination was considered by itself, such was not the case.

Some combinations were unaffected by vacuum and others actually had a decrease of friction in vacuum; notabl 52100 steel had over a 50 percent decrease in vacuum friction.

Six material combinations selected from the referenced work were included in this study. They were stainless steel, aluminum, chromium, silver, cadmium, and nickel. The latter four were platings applied over 1090 steel, hardened to a Rockwell C 60.

The program consisted of two phases. The first phase was a series of 1-minute tests at two load levels in both atmosphere and vacuum, to show any increase in initial vacuum friction. The second phase consisted of running specimens 30 minutes in both atmosphere and vacuum conditions to determine the amount of frictional increase with time.

There was no consistent trend for the initial friction in vacuum to be greater than atmospheric friction during the first phase. There were varying results produced by each metal combination during the second phase. A general trend was for the vacuum friction to be slightly higher than atmospheric friction after running a half hour.

Some results obtained agreed with the referenced work. Some did not.

19. Wallace, W. B., "Vacuum Studies Give Answer to Materials for Space", Product Engineering, 33 (3) 74-75 (February 5, 1962).

General coverage of problems involved: degradation of plastics, evaporation, lubricant stability and test equipment.

20. Buginas, S. J., "Cold Welding in a Vacuum", an Annotated Bibliography", Lockheed Missiles and Space Company, Sunnyvale, California, Special Bibliography, SB-63-5 (March, 1963).

This bibliography contains references issued primarily during the years 1959-1962. It was noted that much of the reported work was oriented around the aspects of friction, seizing and lubrication, rather than welding.

21. Kramer, I. R., and Podlaseck, S. E., "Effect of Vacuum Environment on the Mechanical Behavior of Materials", Final Report No. AFOSR 2139, Martin Company, Baltimore, Maryland, Contract No. AF 49(638)-946 (October, 1961).

Apparatus for conducting fatigue, tensile and creep studies in the pressure range 760 mm mercury to 10^{-8} torr is described. Experimental data are presented for aluminum, single crystals showing that with decreasing pressure fatigue life improves and strength in tension and creep decreases.

22. Ling, S. S., "Welding Aspect of Sliding Friction Between Unlubricated Surfaces", Final Report, Rensselaer Polytechnic Institute, Troy, New York, Contract No. AF 49(638)-67 (June 30, 1960).

This report abstracts material from previous technical notes written on the welding aspect of friction for unlubricated metal surfaces. It also covers a theoretical and experimental investigation of adhesions in which the coefficient of adhesion is related to two important parameters, "activation energy of the process and a time exponent, both of which are dependent upon the degree of cleanliness of the surfaces.

The experimental work was carried out on gold/gold and copper/copper couples. The environment pressures were atmospheric, 10^{-3} and 10^{-6} torr.

23. Simmons, J. C., "Behavior of Materials in Space", Astronautics, Vol. IV, (June, 1959).

A general article on the environmental effects of space on materials. Subjects covered are: surface alterations, material evaporation, accumulation of electrical charges, bulk conductivity changes due to surface alteration, fatigue property due to lack of damping, and friction problems.

24. Hansen, S., Jones, W., and Stephenson, A. R., "Research Program on High-Vacuum Friction", Report AFOSR TR-55-97, Clinton Industries (March 30, 1959).

The friction characteristics of numerous material pairs was investigated in air and in vacuum. The specimens were not outgassed. Measurements were made under various conditions of load, time, and degree of vacuum; the lowest pressure was 10^{-6} torr. Cleaning preparations removed soluble contaminants, but not bonded contaminants or oxides. Results were obtained by measuring the tangential force developed between two blocks which were pressed together under a standardized contact pressure, and slowly oscillated.

No evidence of fundamental relationships was observed. In general, when dissimilar panels were tested the softer material transferred to the harder material, thus masking the effects of the test on the harder material. Under good vacuums the wear products consisted of particles born from th specimen surfaces.

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204	Summary of the Tenth Meeting of the Refractory Composites Working Group, May 5, 1965 (AD 465260)
205	Corrosion Protection of Magnesium and Magnesium Alloys, June 1, 1965 (AD 469906)
206	Beryllium Ingot Sheet, August 10, 1965 (AD 470551)
207	Mechanical and Physical Properties of Invar and Invar-Type Alloys, August 31, 1965 (AD 474255)
208	New Developments in Welding Steels With Yield Strengths Greater Than 150,000 Psi, September 28, 1965 (AD 473484)
209	Materials for Space-Power Liquid Metals Service, October 5, 1965 (AD 473754)
210	Metallurgy and Properties of Thoria-Strengthened Nickel, October 1, 1965 (AD 474854)
211	Recent Developments in Welding Thick Titanium Plate, November 24, 1965 (AD 477403)
212	Summary of the Eleventh Meeting of the Refractory Composites Working Group, April 1, 1966
213	Review of Dimensional Instability in Metals, June 23, 1966 (AD 481620)

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY U. S. Air Force Materials Laboratory Research and Technology Division Wright-Patterson AFB, Ohio 45433

13. ABSTRACT
In this memorandum, the available reports in DMIC which are concerned with welding of metal surfaces in space environments, whether this welding is desirable or undesirable, are reviewed. The phenomenon of surface welding in the space environment is of interest to many for various reasons. Some hope to use the phenomenon for the completion of attachment joints or repairs to spacecraft. Some are concerned because of the possible malfunction of moving components such as bearings, valves, and electrical contacts. Along with numerous other sources of information, this memorandum presents in some detail research and studies performed at Hughes Aircraft and Midwest Research Institute, and the solid-state adhesion of metal studies done at National Research Corporation. However, no effort has been made to correlate and analyze the data that is presented in this memorandum. A section on fundamental studies also is included, along with an annotated bibliography which covers references dealing primarily with lubricants, lubrication, coatings, and test equipment.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Welding	8	3				
Solid-state adhesion	8	3				
Surface welding	8	3				
Joining	8	3				
Stainless steel	1	3				
High-strength steel	1	3				
Superalloys	1	3				
Titanium	1	3				
Copper	1	3				
Light metals	1	3				
Copper-beryllium alloy	1	3				
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Space	5	3				
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